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Studying the Gaseous Phases of Galaxies with Background QSOs

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Abstract. High resolution rest frame UV quasar absorption spectra covering low and high ionization species, as well as the Lyman series lines, provide remarkably detailed information about the gaseous phases of galaxies and their environments. For redshifts less than 1.5, many important chemical transitions remain in the observed ultraviolet wavelength range. I present examples of absorption that arises from lines of sight through a variety of structures, drawn from UV spectra recently obtained with STIS/HST. Even with the greater sensitivity of COS/HST there will be a limit to how many systems can be studied in detail. However, there is a great variety in the morphology of the phases of gas that we observe, even passing through different regions of the same galaxy. In order to compile a fair sample of the gaseous structures present during every epoch of cosmic history, hundreds of systems must be sampled. Multiple lines of sight through the same structures are needed, as well as some probing nearby structures whose luminous hosts have been studied with more standard techniques. Combined with high resolution optical and near-IR ground-based spectra, it will be possible to uniformly study the gaseous morphologies of galaxies of all types through their entire evolutionary histories.

1. Introduction

The tool of quasar absorption line spectroscopy has several distinct advantages over more traditional imaging studies of distant galaxies. Spectra covering absorption lines from numerous chemical elements in various states of ionization can yield detailed information about the physical conditions in the gaseous components of the universe. This is not limited to only the most luminous components. Dwarf galaxies, low surface brightness galaxies, and even intergalactic structures are probed by quasar lines of sight. Quasar absorption lines can be used to study gas during the birth and death of stars and of entire galaxies. The kinematic information contained in high resolution spectra allows us to study processes. This is not just a still picture snapshot; it is more like a short movie. Finally, the same level of detail is available for our study at all redshifts because the same method can be applied using optical and near-IR spectroscopy.

However, the study of quasar absorption lines also presents some challenges if we are to extract from the quasar spectra all of the detailed information about

physical conditions of gas. Imagine if we had to classify a galaxy according to its standard morphological type by zooming in on an image of just a small part of the galaxy. We have to consider carefully what a single line of sight tells us about the global conditions in galaxies. In fact, it should be possible to learn a great deal if we consider the evolution of the ensemble of gaseous structures probed by quasar lines of sight. In order to realize this potential, we must learn to connect absorption signatures to the physical conditions of the phases of gas that produce them, and to the processes that give rise to such signatures in local galaxies.

For the optimal study of the detailed physical conditions along a quasar line of sight we need high resolution spectroscopy covering all rest frame UV transitions. For redshifts less than one, a significant fraction of the key transitions still appear in the ultraviolet. In this proceedings, I review examples of various systems that have been studied in detail, focusing on the question of what additional data would yield a significant advance. The goal is to define capabilities for the optimal UV spectrograph and telescope to be used for such a program.

2. A C IV–Deficient Strong Mg II Absorber?

The $z = 0.99$ absorber toward the quasar PG1634+706 is a strong Mg II absorber, which implies that it is very likely to be within an impact parameter of $35h^{-1}$ kpc of an $\sim L^*$ galaxy (Steidel 1995). It is part of the small subset of Mg II absorbers that have particularly small C IV absorption features, i.e. it is C IV–deficient relative to other strong Mg II absorbers (Churchill et al. 2000). STIS/E230M spectra of this quasar have been obtained by Jannuzi and by Burles, and HIRES/Keck spectra (covering Mg I, Mg II, and Fe II) have been obtained by Churchill and Vogt (2001). The most important transitions are shown in Figure 1. Detailed results of our modeling of this system have been presented by Ding et al. (2002).

The system can be described by a combination of a minimum of four different phases of gas. A phase is a region or regions with density and temperature within some range, spatially separate from other phases. The Mg II absorption arises in clouds that have densities of $\sim 0.01 \text{ cm}^{-3}$. The bulk of the Mg I absorption cannot arise in the same clouds. Instead, we propose that the Mg I is produced by small (~ 100 AU), cool pockets of the interstellar medium. The metallicity of the Mg II and Mg I clouds is about $0.2 \times \text{solar}$. A “broad”, low-metallicity ($< 0.01 \times \text{solar}$) component is required to self-consistently fit Ly α , Ly β , and the higher-order Lyman-series lines. The low metallicity could relate to why this absorber is C IV deficient. Finally, a strong, smooth Si IV absorption profile suggests an additional collisionally ionized phase with $T \sim 60,000$ K, perhaps heated by shocks.

For this system, there are two outstanding issues of particular interest. First, with higher resolution ($R > 100,000$) we could test the narrow Mg I cloud hypothesis. Second, an image of the host galaxy (or those for similar systems) would enable us to see whether an early-type galaxy is responsible for the lack of absorption resembling the Milky Way corona.

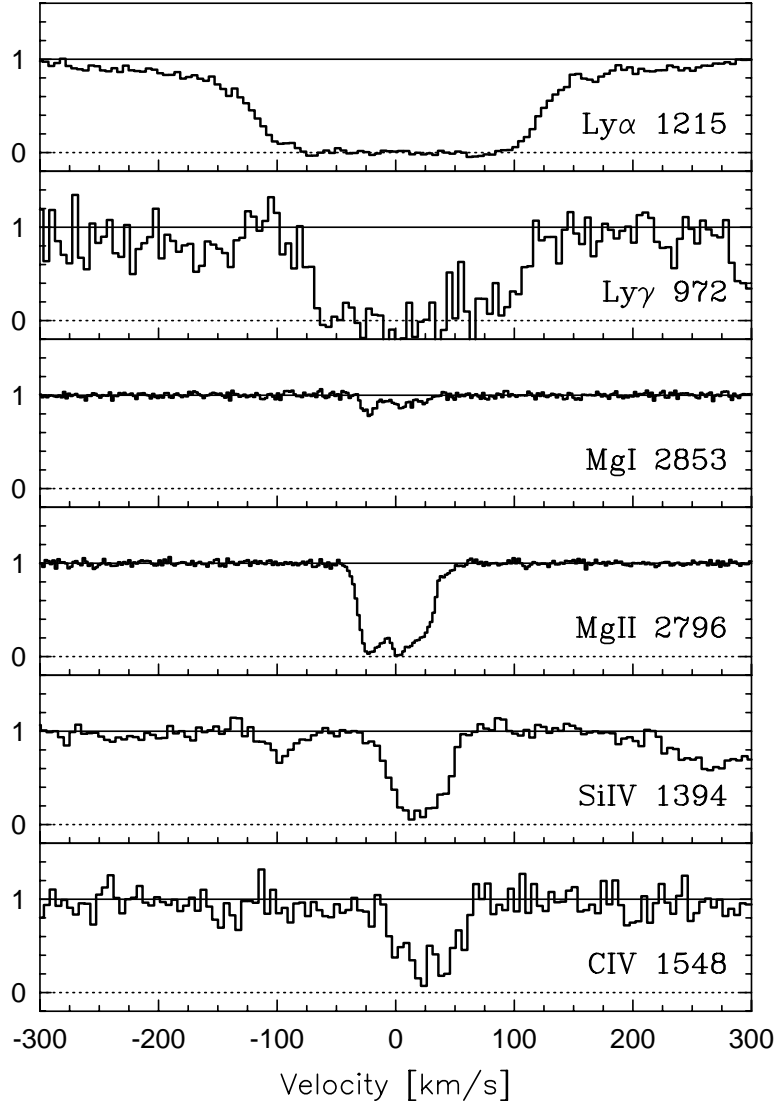


Figure 1. Selected transitions for the $z = 0.9902$ strong MgII system along the PG 1634 + 706 line of sight, presented in velocity space. The velocity zero-point corresponds to the apparent optical depth centroid for the MgII profile. The MgI and MgII profiles were obtained with HIRES/Keck, with $R = 45,000$ (P.I. Churchill), and the other transitions were observed with STIS/HST, with $R = 30,000$ (P.I.'s Jannuzi and Burles).

3. A Redshift One Galaxy Group?

The $z \sim 0.93$ systems in the PG 1206 + 459 line of sight are the subject of a separate contribution in this volume by Jie Ding, and therefore no detail or figures will be presented here. Three distinct systems (two strong MgII and one weak MgII) are apparent at $z = 0.925$, $z = 0.928$, and $z = 0.934$, an overall velocity spread of just over 1000 km s^{-1} . This is likely to be a group of galaxies, with the three systems arising in three very different types of galaxy hosts. The study of these systems would be aided by higher S/N since there are suggestions of abundance pattern variations. Understanding of the phases giving rise to high ionization absorption would be much better constrained if a high resolution spectrum covering the OVI transition was obtained.

4. A Pair of Dwarf Galaxies?

The $z = 1.04$ Absorber Toward PG 1634 + 706 is a multiple cloud, weak MgII absorber, with two sets (kinematic subsystems) of low ionization “clouds” separated by $\sim 150 \text{ km s}^{-1}$. Each of the subsystems has an OVI absorption profile offset by $\sim 50 \text{ km s}^{-1}$. Profiles for key transitions from the STIS/HST and HIRES/Keck spectra are shown in Figure 2. This system was modeled by Zonak et al. (2002), and the results are summarized here.

The MgII clouds have metallicity $< 0.03 \times \text{solar}$, constrained by a partial Lyman limit break. Although SiIV has the same kinematic structure as MgII in the stronger subsystem, the clouds appear to be offset by velocities ranging from $3\text{--}5 \text{ km s}^{-1}$. This could be related to an HII region flow, but the interpretation of the multiple cloud structure remains unclear. The SiIII profile is smooth, but unsaturated, and is stronger than can be explained by the combination of the MgII and SiIV cloud phases. This suggests a collisional ionization mechanism for producing SiIII. The Ly α profile requires two additional photoionized phases that can also produce the broad OVI profiles.

The low metallicity and the kinematics of the two subsystems suggest that two dwarf galaxies and their halos could be responsible. The lower ionization phases would arise in the inner regions of the dwarfs, and the offset higher ionization phases from their halos.

Very little is known about the expected absorption signature of dwarf galaxies. If quasar absorption line probes through nearby dwarfs were available, this mystery would be quickly solved. However, this would require that some fainter quasars were accessible for high resolution spectroscopy.

5. A Variety of Weak MgII Absorbers

Figure 3 shows selected transitions for the three single-cloud, weak MgII absorbers at $z = 0.65$, $z = 0.81$, and $z = 0.90$ along the same quasar PG 1634+706 line of sight. Unlike the strong MgII absorbers, single-cloud, weak MgII absorbers are generally not found within 50 kpc of L^* galaxies. Rigby, Charlton, & Churchill (2002) found, based on a larger sample for which lower resolution FOS spectra were available, that they cannot be far below solar metallicity. They also found that at least a subset of these absorbers are very small in di-

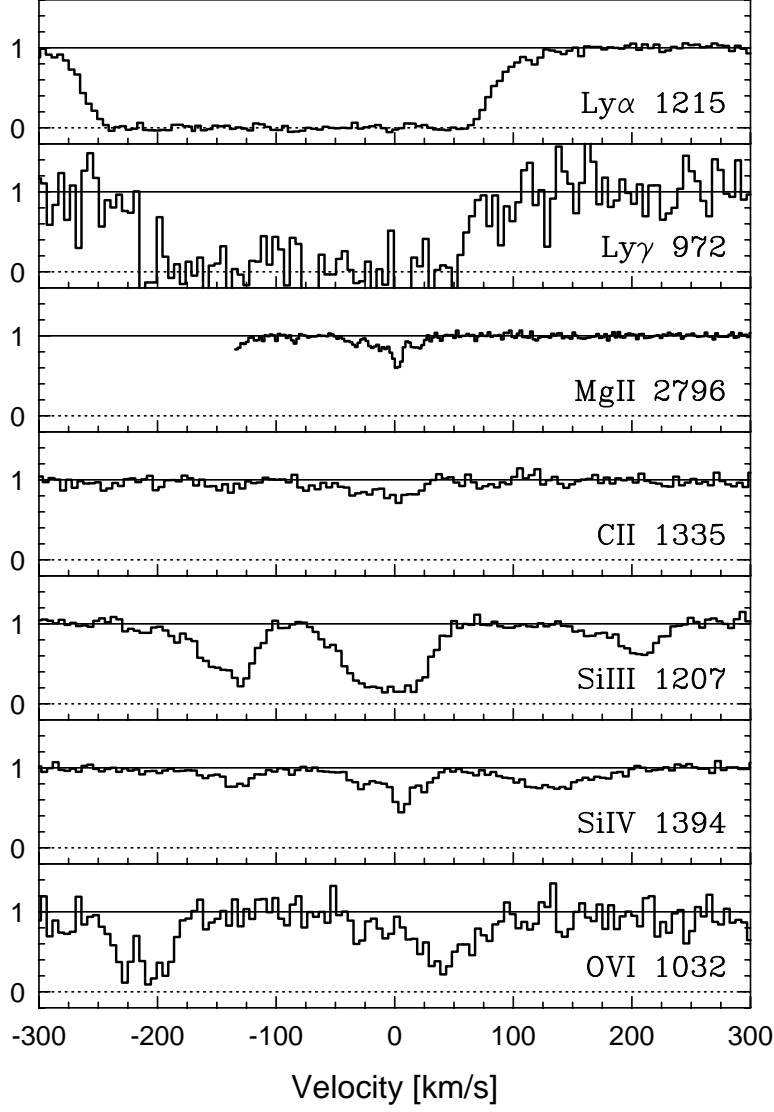


Figure 2. Selected transitions for the $z = 1.0414$ multiple-cloud, weak MgII system along the PG 1634 + 706 line of sight, presented in velocity space. These are taken from the same spectra noted in the Figure 1 caption.

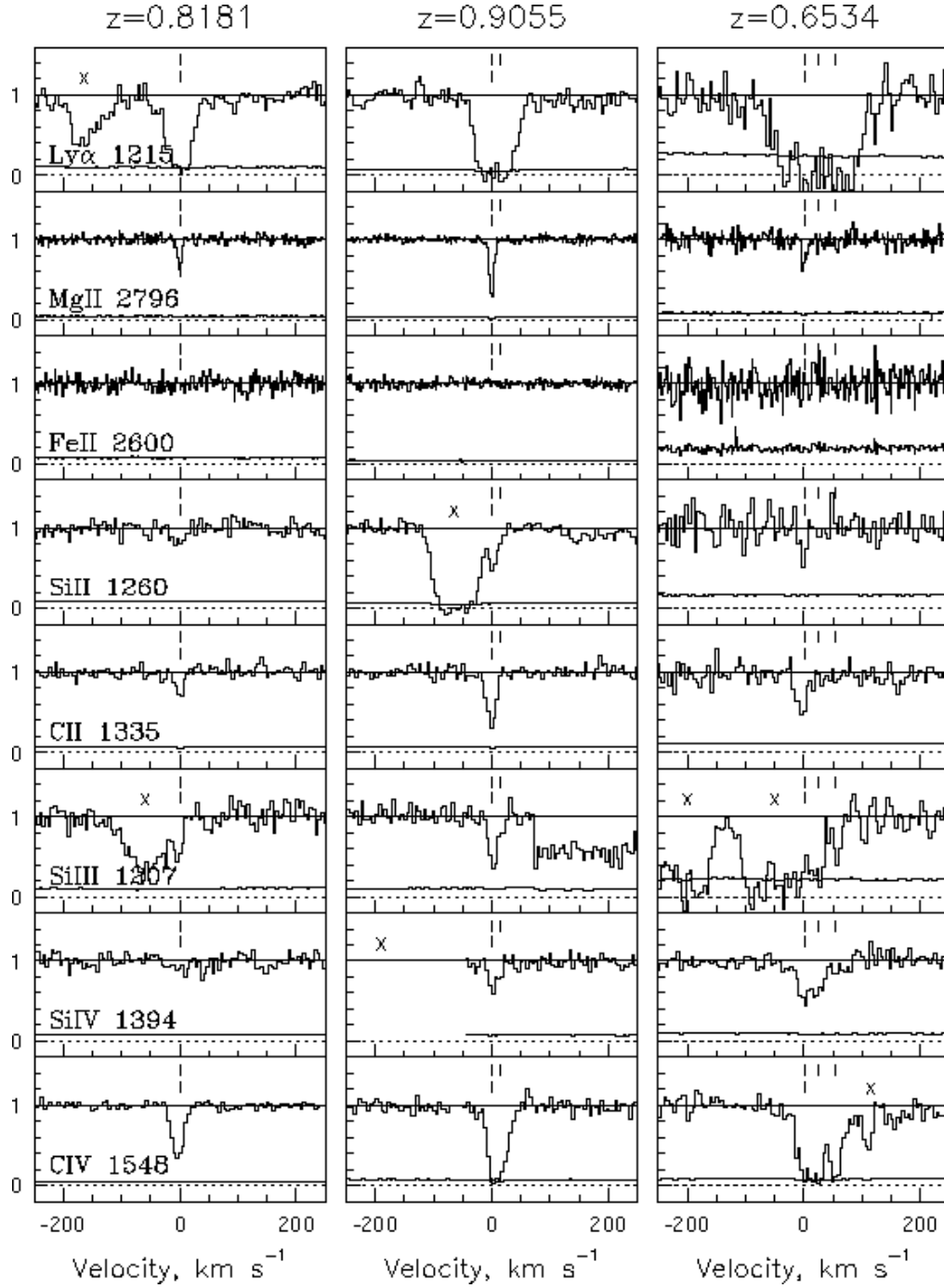


Figure 3. A comparison of selected transitions for the three single-cloud, weak MgII absorbers along the PG1634 + 706 line of sight. The spectra from which these were extracted are referenced in the Figure 1 caption.

mension. Detailed models of the three PG 1634 + 706 single-cloud, weak MgII absorbers were presented in Charlton et al. (2002).

The $z = 0.81$ weak MgII absorber is the kinematically simplest along this line of sight. The CIV absorption is relatively weak. It was not even detected in a low resolution FOS spectrum. The Ly α profile constrains the metallicity to be supersolar, and the ionization conditions indicate that the low ionization phase is sub-parsec scale. Despite the CIV being weak, the broad shape of its profile cannot be fit by the MgII cloud. The high ionization phase could be collisionally ionized, but photoionization is more likely, with a cloud size of ~ 100 pc. The high ionization phase could surround or be surrounded by the low ionization gas.

If the high ionization material is a thicker shell surrounding a small low ionization pocket then we would expect to see many systems with only the high ionization phase. A large statistical sample is needed to determine the geometry. To distinguish between collisional ionization and photoionization, coverage of the OVI transition is key.

In contrast, the $z = 0.90$ weak MgII absorber has relatively strong CIV. A low ionization phase has supersolar metallicity and a cloud size of ~ 50 pc. The CIV and NV require a separate, broader cloud, which is consistent with photoionization and not with collisional ionization. Also, in this case, an additional offset high ionization cloud is required to fit the blue wing of the CIV and the Ly α , which is not centered on the MgII. The CIV equivalent width could be large in this case partly because the line of sight passed through a separate cloud at a different velocity, and not because the centered CIV cloud has special physical conditions.

The CIV profile associated with the $z = 0.65$ weak MgII absorber has distinct subcomponent structure, and therefore a large equivalent width. The Ly α is also quite strong for this system, possibly also because of the large kinematic spread. It is centered on the CIV and not on the single MgII component. The low ionization phase is poorly constrained, but its metallicity must exceed $0.1 \times$ solar. The three CIV components arise in high ionization, kiloparsec-scale structures, which are likely to be photoionized.

What are these weak, single-cloud MgII absorbers? The small size constraints on the low ionization phases implies that there must be huge numbers of the host structures. In fact, to account for the observed number of weak, single-cloud MgII absorbers, per unit redshift, there must be more than a million hosts for every L^* galaxy in the universe. Yet, these are not associated with L^* galaxies. They appear to be self-enriched pockets of higher density material embedded in higher ionization, more diffuse gas. Rigby et al. (2002) discuss the origin of the weak MgII absorbers at length. Their two most likely explanations are small traces of gas in fading remnants of Population III star clusters and fragments of supernova shells in faint blue dwarf galaxies.

A number of new capabilities would help to constrain the properties of this intriguing class of object. Double line of sight observations at a scale of parsecs, though they could not be done for many systems, would provide an essential check on size constraints for these weak MgII absorbers. Nearby weak MgII absorbers must be identified so that narrow band imaging can be used to discover if hosts are dwarf galaxies or isolated star clusters. Of course, a

large statistical sample would clarify whether there are different classes of weak, single-cloud MgII absorbers, with different types of hosts.

6. Conclusions

The small sample of systems presented here demonstrates great promise for learning about the detailed physical conditions in a variety of gaseous environments. For these systems, the data have some limitations and, as a result, some questions remain unanswered. These highlight the need for additional UV spectroscopy capabilities. I conclude by presenting a “wish list” if we aim to construct the dynamical history of the ensemble of galaxies and gaseous structures:

- hundreds of systems, or even thousands!
- cover all key chemical species from the rest frame ultraviolet
- study many systems that are at low enough redshift to image their galaxy hosts; these serve as a calibrator for higher redshift systems
- higher spectral resolution ($R = 100,000$ or even higher) for a subset of the systems in order to resolve interstellar medium features
- high signal-to-noise (> 20) for a subset to enable abundance pattern studies
- multiple lines of sight through the same objects
- a separate, detailed study of the interstellar medium of the Milky Way and of nearby galaxies using the same techniques

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